Extreme Heat and Air Pollution Risks for Early Childhood Development in Latin America and the Caribbean

Preliminary draft

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Abstract

Latin America and the Caribbean (LAC) is characterized by high and unequal exposure to climatic and environmental hazards. Children under five are particularly vulnerable. Specifically, exposure to air pollution and extreme heat can exacerbate health risks: sudden temperature increases can lead to heat stroke, dehydration, and even death, while warmer temperatures heighten the transmission of vector-borne diseases. Extreme temperatures can also reduce food production quality and quantity, contributing to malnutrition. Air pollution is linked to thousands of child deaths annually and to a range of non-communicable diseases (e.g., asthma, cancer, neurodevelopmental and mental health disorders), which disproportionately affect poorer households and often have long-term effects. Exposure to poor air quality and rising temperatures can also deepen poverty, exacerbate inequalities, and have intergenerational impacts, potentially increasing conflicts over time. This report addresses the significant challenges faced by LAC due to extreme heat and air pollution exposure on early childhood development (in utero to age 5). First, it introduces a framework for understanding how exposure can impact various dimensions of early childhood development, such as birth outcomes, mental health, physical health, cognitive development, and physical growth. These effects are likely to interact dynamically over a child's lifecycle, affecting development stages in early life and beyond age five, within an ecological framework that includes families, communities, services, and infrastructure, which may mediate or intensify these impacts. Second, by considering the spatial distribution of the child population, air pollution (PM 2.5), temperature (UTCI), and economic vulnerabilities in LAC, the report provides measures and rankings of climatic and pollution burdens for children across economies in the region. Finally, it presents evidence on the effects of climatic and pollution risks on child development under age five and concludes with policy recommendations for LAC.

Keywords: Climate, Air Pollution, Extreme Heat, Early Childhood Development, Health, Nutrition, Education

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1 THE CHALLENGE: EXTREME TEMPERATURE, AND AIR POLLUTION TRENDS AND CHANGES IN EARLY CHILDHOOD DEVELOPMENT

1.1 Overview

Latin America and the Caribbean (LAC) regions are facing increasing trends in exposure to air pollution and extreme temperatures (UNOCHA and UNDRR 2023, 8). Children in Latin America's mega-cities are exposed to high levels of outdoor air pollution, and indoor air pollution is also a concern (Laborde et al. 2015, 202).[1] A case–control study conducted in 14 districts in the City of São Paulo, Brazil found increasing risks of early neonatal death with higher exposure to traffic-related air pollution, such that mothers exposed to the highest quartile of a distance-weighted traffic-density measure compared with those less exposed exhibited approximately 50% increased mortality risks (De Medeiros et al. 2009). Research elsewhere has linked prenatal exposures to poorer birth and developmental outcomes (for birth outcomes, see Liu, Miao, et al. (2022) and Liu, Behrman, et al. (2022); for a review on birth and early childhood developmental and health outcomes, see Landrigan et al. (2019)). Temperatures are rising—a shift that is increasing the frequency and intensity of severe weather-related events and creating conditions conducive to the spread of mosquito-borne illness (PAHO 2024; UNECLAC 2024b; UNOCHA and UNDRR 2023, 8–9).

Moreover, in Latin America and the Caribbean (LAC) "a complex environment of risk drivers" exacerbates the potential impact of climatic and pollution exposure (UNOCHA and UNDRR 2023, 8). Drivers include dense urban populations in cities highly vulnerable to natural hazards; a "double trap" of low growth and high levels of inequality; political instability; population displacement and large-scale migration; and high rates of violence that can exacerbate inequality and inhibit disaster responses (PAHO 2024; UNECLAC 2023, 13; UNOCHA and UNDRR 2023, 8–9). Social and economic risk drivers may compound vulnerability to climatic and environmental hazards, especially for communities and individuals facing economic, social or political marginalization and associated barriers to accessing infrastructure and public services.

Children's exposure to air pollution and rising temperatures will impact their development and short- and long-term outcomes, which can exacerbate inequalities in the region. Children are more vulnerable to climatic and environmental hazards on multiple dimensions compared to adults. A recent UNICEF report highlights reasons for children's particular vulnerability to climate hazards and associated disasters (Rees et al. 2021, 11):

> They are physically more vulnerable, and less able to withstand and survive shocks such as floods, droughts, severe weather and heatwaves...They are more at risk of death compared with adults from diseases that are likely to be exacerbated by climate change, such as malaria and dengue. They have their whole life ahead of them—impacts resulting from climate and environmental exposure at a young age

1. Laborde et al. (2015) review a variety of other important pollutants in the region that are important for children, including lead, asbestos, mercury, and arsenic exposures. See UNECLAC (2024a) for trends in air pollution exposure.

can result in lifetime consequences.

Rees et al. (2021, 11) and Landrigan et al. (2019, 2390–2391) also highlight children's physiological vulnerability to toxic substances, such as lead and other forms of pollution, sometimes at even lower doses than adults. At the earliest stages of life, pollution exposures "can result in lasting injury to cells and tissues that increases risk of disease in childhood and can also reverberate across the life span" and can "undermine efforts to enhance children's development though improved nutrition, early learning and better health care." (2390–2391).

These exposures are widespread and cumulative. UNICEF estimates that more than 99% of children have exposure to at least one event related to climatic and environmental hazards, shocks and stresses. The same report informs that 1.7 billion children are exposed to at least three and 80 million to at least six of these events (Rees et al. 2021). The Caribbean is one of the regions with the highest risks for these cumulative effects.

The lack of public services to alleviate the effects of these shocks might create more inequalities and exacerbate existing social vulnerabilities already widespread in the region.

This report focuses on the consequences of air pollution and extreme temperatures exposures in LAC for children in utero until year five, in connection with other vulnerability factors such as poverty and service accessibility. Other climatic and environmental factors are also potentially important for the welfare of children in this region, but due to data availability, and limited literature scope, we will not analyze them here. [2]

1

1.2 Theoretical framework

We utilize the framework in Figure 1.1 and highlight several critical features relevant to this report.

First, child development encompasses multiple components, as illustrated in the bottom (gray) box in the figure. We identify five key dimensions: birth outcomes, mental health, physical health, cognitive development, and physical development. These components can interact either contemporaneously or over time (e.g., the dynamic complementarities highlighted by Cunha and Heckman (2008)). While our framework focuses on dimensions discussed in our literature review, we acknowledge that other important aspects of early childhood development (ECD) are not addressed here. For instance, the Nurturing Care Framework includes health, nutrition, learning, relationships, and safety and security (Black et al. (2021)). We limit our discussion to literature on the effects of air pollution

2. For example, Carvalho (2024) cites deforestation first among the "top five" environmental issues facing South America. Between 1990 and 2010, South America experienced the world's highest annual rate of forest loss; since 2010, the region has experienced the second largest highest annual forest loss rate in the world, after Africa (Alves 2023; FAO 2020). Research elsewhere has linked deforestation to poorer birth outcomes and early health outcomes for children, possibly attributable to malaria exposures, and reduced dietary diversity among children (Fuentes Cordoba 2024; Galway, Acharya, and Jones 2018). The other key environmental factors highlighted by Carvalho (2024) are soil erosion, glacial melting, water pollution and scarcity, and sea level rise. We will touch on these factors as they connect to the factors that we do consider empirically in this paper, and in our discussion in the concluding section.

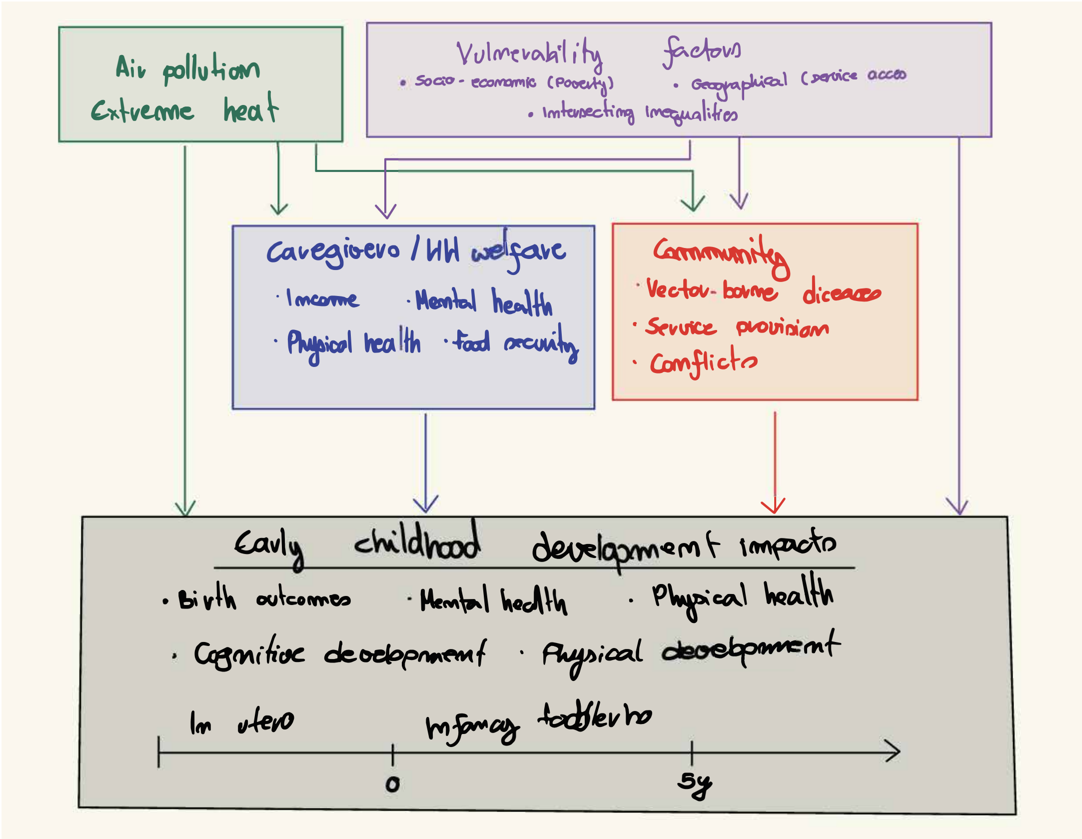
and extreme heat on ECD, recognizing that, despite growing research, studies addressing all ECD dimensions remain scarce.

Second, child development is a dynamic process with several life-cycle stages within the neo-natal, infancy, and toddlerhood phases (ages 0-5). In this report, we focus on impacts occurring from the in-utero period up to age five. The importance of different developmental components may vary across ages within stages and across these stages, so empirical findings and their implications may also differ by age and stage. Although this report does not cover stages beyond age five, it is essential to consider that shocks experienced by children aged five or younger can significantly impact later stages of development.

Third, extreme temperatures and air pollution can directly and indirectly impact ECD dimensions. The arrow in Figure 1.1 linking the green and gray boxes illustrate the direct effects of exposure on development, such as biological impacts like heat stress and respiratory complications. Indirect effects stem from influences on caregivers/households (blue box) and communities (red box) that may be amplified by vulnerability factors (purple box). For instance, extreme heat can lead to crop failure, resulting in negative income shocks that reduce household investment in children's human capital and nutrition, particularly for children living in greater poverty and with lesser access to health and other services. An important aspect of these indirect effects is the potential for interaction among mechanisms, which may jointly impact various aspects of child development. We limit the mechanisms in the framework to those discussed in our literature review.

Fourth, both extreme temperatures and air pollution affect child development directly and indirectly through the same ecological layers, although the magnitude and specific mechanisms may vary. For example, indirect effects from vector-borne diseases may be significant for extreme temperatures but are unlikely mechanisms for air pollution.

Figure 1.1: Environment and children framework sketch



Note: This framework sketch focuses on extreme temperatures, air pollution exposures, and early childhood development (ECD) from in utero to age 5. The green box represents environmental factors, specifically air pollution and extreme heat exposure, that influence ECD directly and indirectly. The purple box captures vulnerability factors that may affect children's development and the impacts of environmental factors. The blue box contains mechanisms related to caregivers and household welfare that impact ECD. The red box highlights community-level mechanisms affecting ECD outcomes. The gray box represents various dimensions of children's development influenced by the factors and mechanisms outlined in the boxes above.

1.3 Report objectives and outline

In this report, we provide novel data and identify hotspots[3] in LAC where air pollution and extreme heat overlap with geographical distributions of economic inequality and children. We combine child population distributions with gridded data on the distributions of air pollution by aerosols, and gridded data on share of time experiencing extreme heat exposure. Using these data and building on Feng et al. (2024) and Santos et al. (2024), we compute cell-level, sub-national, and national distributions of air pollution by aerosols and extreme heat exposures for children for countries in Latin America and the Caribbean.

Given this information, we provide national and regional rankings in Latin America and the Caribbean for the countries and regions where children face the greatest to the least extreme heat, and pollution burdens. These ranking compare the national and regional child-population weighted climatic burden measures, and rely on the within-country and regional

3. *Note: we have not done the hot spot analysis, but this is a possible direction if we want to proceed in this way. We have in Figures* **??** *and* **??** *and Table 3.5 computed child-specific national heat and pollution exposure burdens, aggregated up from gridded data. Building on these and the Poverty Map shown in* **??**, *we could identify hotpots as proposed below.*

distributions of children and the distributions of climatic burdens. Furthermore, we identify countries and regions that rank jointly high in multiple dimensions of climatic burdens, and combine the gridded spatial distributions of climatic exposures burdens for children with the spatial distribution of poverty and service accessibility in Latin America and the Caribbean to pinpoint areas in Latin America and the Caribbean where children are most at risk of climatic burdens.

This report is structured as follows. Section 2 describes our data and presents a distributional analysis of hazards and the burdens facing children in LAC. In Section 2, we present first a distributional analysis of the location of climate events and the intensity of these events. Second, we present a population distribution analysis of children in LAC. Third, we map poverty indices. Finally, we overlay these analyses to identify the areas where we have the presence of children, economic vulnerability, and adverse climate events. This exercise can inform the policy, government, and NGO communities about important "hot spots" of vulnerability for targeting social services to alleviate exposure consequences.

Having presented exposures, in Section 3 we turn to a reflection on likely outcomes of exposures by referencing existing research on the effects of exposure to air pollution and extreme heat on early child development. We review literature on on two groups of outcomes: Health and nutrition; and Learning, cognitive development, relationships and behaviors. The age range of our analysis is from the intero period to 5 years old, as we focus on early children development. Finally, we review literature on prevention and mitigation strategies—infrastructure and resilience.

In section 4 we describe how countries are investing on tools to deal with the rising climate crisis. After that, We give recommendation on two dimensions. First, we discuss how the region can implement policies to alleviate exposure to air pollution and extreme heat. Second, how can public service alleviate the effects of exposure to increasing air pollution and temperature levels.

Section 5 concludes. Here, we reflect on key findings and policy recommendations, and discuss key areas in need of further evidence. We acknowledge that the scope of climatic and environmental hazards affecting children is broader than what we are able to analyze here. Drawing on other literature, we reflect briefly here on potential implications for young children of other environmental issues such as sea-level rise, vector-borne diseases, deforestation, and other related issues.

2 Distribution of climatic shocks

While there are many sources that provide the distribution of climatic burdens regionally and globally, this report is the first to provide child-population-weighted distribution of climatic burdens for Latin America and Caribbean countries. Feng et al. (2024), which studies heat exposure changes for children in China, is the first paper to compute child-population-specific changes in heat exposure using gridded temperature and subnational child population data. Santos et al. (2024) computes global population weighted distributions for air pollution by aerosol exposures, but does not focus on children.

2.1 Data and methods for computing child population climatic burdens

In this section describe our sources for population, air pollution, and extreme temperatures data. For a particular subnational, national and supranational region, we compute the child population weighted pollution or heat exposure measure using the distribution of children jointly with the distribution of climatic burdens at the finest level of geography where data is available. Our statistics informs policy makers not on where pollution, extreme temperatures are concentrated, but where a specific population group, in this case children 0 to 5, face different magnitudes of climatic exposures. Given that the spatial distribution of children in Latin America and the Caribbean might not overlap with the spatial distribution of climatic burdens, it is essential to combine the population distribution and climatic distribution data jointly to identify locations where children are most at risk.

2.1.1 Population data

We generate cell-specific global population estimates based on the WorldPop population estimates dataset. The gridded WorldPop data provides total population estimates at 30 arc-second grids ($\sim$ 1km at the equator), and is aggregated based on up to administrative level 6 population data from global economies. We aggregate the raw cell-level data

2.1.2 Vulnerability factor datasets

Poverty information

Public service access

2.1.3 Climatic and environmental hazard data

Air pollution data. Atmospheric pollution by aerosols is important to human health and well-being, especially when there is a higher concentration of $PM_{2.5}$ particles that are smaller then 2.5 micrometers (Jacobson 2002). Aerosol Optical Depth (AOD) is a satellite-based measure that captures the composition, sizes and concentration of aerosols by measuring the magnitudes atmospheric light reflection and absorption across the globe (Lenoble, Remer, and Tanre 2013).

Scaled between 0 to 1 [4], an AOD value that is less than 0.1 indicates crystal clear sky and clear satellite to earth surface visibility. In contrast, a AOD value close to 1 indicates very hazy conditions (NASA Earth Observatory 2024).

Following Santos et al. (2024), we use AOD measurements based on images collected by the TERRA satellite with its MODIS instruments (Xiong et al. 2020), and we access the data via the NASA EarthData data collection and using the OpenDAP protocol (Cornillon, Gallagher, and Sgouros 2003). Within each $1^\circ \times 1^\circ$ longitude–latitude grid (cell), we compute average daily AOD values based on the subset of the daily AOD measurement vector that fall within the geographical boundaries of each cell on that day. Using the cell-specific vectors of average daily AOD measurements from a year, we compute annual average AOD exposures for each cell.

Extreme heat data. We utilize the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalyses of the global climate: the ERA5-HEAT dataset (Napoli 2020). ERA5-HEAT, a distinct advancement from its predecessors, offers hourly data on numerous climate variables with a spatial resolution of 0.25 degrees one of which we utilize is Universal Thermal Climate Index (UTCI). UTCI provides an integrative measure of the human-perceived equivalent temperature, taking into account factors like air temperature, humidity, wind speed, and radiant heat (Bröde et al. 2012; Jendritzky, Dear, and Havenith 2012; Jendritzky and Höppe 2017).

Following Feng et al. (2024), within a particular span of time at a particular gridded location, we compute extreme temperature facing the average child, measured in units of share of time individuals in this location are exposed to extreme temperature, considering multiple temperature thresholds capturing different magnitudes of heat stress.

2.2 Climatic burdens for children

2.2.1 Air pollution

Figure 3.1 presents the LAC-specific relative dispersion of air pollution by aerosols as measured by Aerosol Optical Depth (AOD). We compute annual average AOD for each cell ($1^\circ \times 1^\circ$ longitude–latitude grid) showed in 3.10 and then generate country-specific AOD as cell-population weighted averages. For population data, we use the within-country distribution of children between ages 0 to 5. The colors in the figure here correspond to levels of excess aerosol burden, a value of 0.5 (-0.5) indicates that a country's AOD measure is 50 percent greater (smaller) than the *global* weighted mean (note: this will be corrected to LAC-specific mean in the future). Darker shades of green (red) correspond to greater magnitudes of negative (positive) excess burdens.

Figure 3.1 and Table 3.5 show that Chile has the least age 0-5 child-specific air pollution and Colombia has the highest. Colombia's child-specific AOD value is 3.2 times larger that of Chile's. Among wealthier countries—following World Bank country-income group classification—Chile and Uruguay are ranked among the top five in terms of having the lowest

4. The values are typically within this range which jsutify why NASA use it as the range of analysis. However, negative values and values above 1 are possible. Negative values can be understood as missing or numbers very close to zero. Numbers above 1 indicate extremely hazy conditions

child air pollution exposure, but Guyana and Panama are ranked in the bottom tercile of countries. Venezuela and Ecuador, along with Colombia, have the highest level of child-specific air pollution levels.

2.2.2 Extreme temperatures

Figure ?? presents the LAC-specific relative dispersion of heat exposure. We compute annual average heat exposure for each cell ($1° \times 1°$ longitude–latitude grid) and then generate country-specific heat exposure as cell-population weighted averages. The measure of heat we use is the share of hours in 2010 in each cell during which temperature was in excess of UTCI 32 °C, which is the threshold for strong heat stress. For population data, we use the within-country distribution of children between ages 0 to 5. The colors in the figure here correspond to levels of excess heat exposure, a value of 0.5 (-0.5) indicates that a country's heat exposure measure is 50 percent greater (smaller) than the LAC-specific weighted mean. Darker shades of red correspond to greater magnitudes positive excess heat burdens.

Figure ?? and Table 3.5 show that Chile has the second lowest age 0-5 child-specific extreme heat exposure. During 2010, the average child experienced UTCI heat exposure in excess of 32 °C for only 0.6% of their total hours. In contrast, children in Guyana, Suriname, and French Guiana experience more than one quarter of their 2010 hours in excess of 32 °C. Similar to Chile, a number of countries have both low extreme heat and pollution exposure for children, Uruguay, for example, is ranked number 4 and 6 for having the least child-specific air pollution and extreme heat exposure. In contrast, Venezuela is ranked 35 and 33 for having some of the highest child-specific air pollution and extreme heat exposures. Pollution and heat exposure do not necessarily align, Haiti and Honduras, is ranked as having the 11th and 8th lowest level of air pollution for children, but have the 31st and 26st highest level of heat exposure.

2.3 Hotspot analysis

In-progress. We combine prior data to analyze overlapping risks facing children in LAC. We will combine climatic risk with also economic risks, and we plan to include existing subnational economic inequality distributional maps, including for example what is shown in Figure ??, sourced from CEPAL.

3 Linking exposures to likely impacts on the under-five population

In this section we summarize selected studies on the impacts of climatic, pollution and natural disasters on different components of child development for children five and younger. We focus on studies from LAC, but include some studies from other parts of the world particularly for topics for which we have not been able to find many studies on LAC

3.1 Nutrition and growth

3.1.1 Pollution

Rangel and Vogl (2019) use data from satellite-based fire-detection systems, air monitors, and vital records in Brazil to study how in-utero exposure to smoke from sugarcane harvest fires affects birth outcomes. Exploiting daily changes in fire locations and wind directions for identification, they find that late-pregnancy smoke exposure decreases birthweight, gestational length, and in-utero survival. Being upwind versus downwind of fires, for example, increases birthweight by 98 grams and gestation by 0.35 weeks. Fires less associated with smoke exposure, on the other hand, predict improved health, highlighting the importance of disentangling pollution from its economic correlates.

3.1.2 Temperature

Bakhtsiyarava et al. (2022) study the impacts of prenatal exposure to extreme temperature on children birthweight in Latin American cities. The authors combine monthly average temperature data with birth record of cities in Brazil, Mexico, and Chile from 2010 and 2015 to investigate the correlation between temperature and birth outcomes. The study finds that there is a negative correlation between higher temperature exposure and lower birthweight, with the cumulative exposure effects being driven mainly by the exposure faced in the last trimester of pregnancy.

Sanchez (2018) studies the impact of exposure to unusual cold days on children height-for-age at the age of 5 in the Peruvian Highlands. The empirical approach relies on variations in temperature exposure among children within clusters, which are determined by differences in birth dates, specifically at the monthly level, in regions where frosts are common. The author find that additional exposure to unusually cold months during the first three years of a child's life reduces their height-for-age at 5 years old by 2.7%, with this effect disappearing by age 8.

3.2 Physical and Mental Health

A case–control study conducted in 14 districts in the City of São Paulo, Brazil found increasing risk of early neonatal death with higher exposure to traffic-related air pollution, such that mothers exposed to the highest quartile of a distance-weighted traffic density measure compared with those less exposed exhibited approximately 50% increased risk (De Medeiros et al. 2009)

3.2.1 Pollution

3.2.2 Temperature

3.3 Relationships and behaviors

3.3.1 Pollution

3.3.2 Temperature

Wu et al. (2023) study the effects of early childhood climate on home environment. By examining data on children's household conditions, the study explores how variations in climate during the first years of life impact the quality of home environments in rural China. The findings reveal that households in regions with harsher climates tend to have lower-quality home environments.

3.4 Safety and security

3.4.1 Pollution

3.4.2 Temperature

3.5 Learning and cognitive development

3.5.1 Pollution

3.5.2 Temperature

Odo et al. (2023)'s cross-sectional analysis examines the relationship between long-term exposure to ambient air pollution and cognitive development in children aged 3–4 years across 12 low- and middle-income countries. Using data from a large sample, the study investigates the potential impact of air pollution on cognitive abilities in early childhood. The findings suggest a concerning association between higher levels of ambient air pollution and reduced cognitive development at age 3-4, highlighting the importance of addressing air quality issues in low- and middle-income countries to promote optimal cognitive outcomes for children during their formative years.

Sanchez (2018) investigates the effects of children exposure to cold days within the first three years of life on children cognitive achievement and socio-emotional competencies. The study leverages differences in temperature exposure among children within clusters, based on variations in birth dates at the monthly level, specifically in colder areas. He finds that there is no overall impact of unusual cold days on cognitive achievement and socio-emotional outcomes. However, when focusing on girls, the author finds a negative correlation between cold days exposure and cognitive achievement, with a standardised coefficient of -1.5 per cent.

Wu et al. (2023) study the effects of early childhood climate on cognitive development. By examining data on children's cognitive abilities and household conditions, the study explores how variations in climate during the first years of life impact cognitive development and the quality of home environments in rural China. The findings reveal that exposure to more extreme weather conditions, particularly colder temperatures, during early childhood is associated with adverse effects on cognitive development, such as reduced cognitive abilities before age 5. Furthermore, the findings suggesting lower-quality home environments in regions with harsher climates can potentially exacerbate the negative impact on children's cognitive development.

3.6 Infrastructure

Some countries in LAC have been considering climate resilience in their action plan, however the involvement of the region should increase. The Sixteenth session of the Conference of the Parties (COP 16), defined the National Adaptation Plans (NAP) in order to help countries to develop strategies towards climate resilience. According to (OECD 2023) only 12 out of 33 countries of the regions has submitted their NAP to UN. An alternative to it is the inclusion of the climate transition into the National Determined Contributions (NDCs) or their Long-Term Strategies (LTS). Even though these are alternatives to the commitment to climate resilience transition, nor much progress has been observed in the last years (OECD 2023). The active involvement of the countries in the region is the only path for a sustainable transition to climate resilient enviroments.

Climate resilience is a key factor that can help to alleviate the effects of climatic and environmental shocks on children's development. LAC increasing risk to climate shocks indicates the environmental events discussed before will generate costs to children development in the region. Developing resilience in the precaution and defense can lead to full avoidance of some events, as alerts of poor air pollution quality, or the alleviation of it, as temperature controlling system in hot or cold days.

Climate resilient infrastructure can also help to reduce climate change drivers through sustainable strategies. It is important to consider the sustainable dimension of these facilities, as resource management it is an important topic to reduce climate change pace. For example, this facilities can be equipped with more efficient/sustainable water, emissions and energy system. The installation of solar panels, water storage mechanism or policies to use these resources efficiently can avoid future scarcity in periods of droughts or energy restrictions.

An important aspect for shock prevention is the development of early warning and civil protection system. The unpredictability nature of climatic events makes necessary the existence of prevention system to evacuate or prepare communities to receive these shocks. In the case of natural disasters, this can have a clear and direct impact of saving children's lives, but also help to alleviate household losses by anticipating the events. For air pollution, having a system that can inform households of excessive exposure could avoid health impacts trough the use of masks or avoiding exposure by staying at home.

Specific sector approaches are important to prioritize investments. For example, education providers should be equipped with flood defense mechanism and temperature regulators to minimize negative learning impacts. For the health facilities, the priority is to to provide enough resources to accommodate possible increase on demand for health services and climate related illness when these events happen.

The sector can also contribute with the alleviation of climate change trough specific approaches. Education and health facilities could be helpful in informing agents on the risks, precautions against and information on climate change and its related issues. Another important aspect for early childhood development is developing infrastructures that can guarantee the provisions of these services after climate shocks.

3.6.1 Pollution

3.6.2 Temperature

4 Policy Recommendations

The above discussion suggests at least three major areas of policy.

First, *information* is critical. For governments to develop the most effective policies, they need good information on a fairly localized level about both the distribution of children and about the distributions of different risk factors. There are great heterogeneities within countries so that regionally targeted policies may be necessary to most effectively address risks for children given budgetary constraints. There are also other important information issues. Improvements in warning systems for extreme climate and natural-disaster events, for example, may significantly reduce the negative impacts of such events.

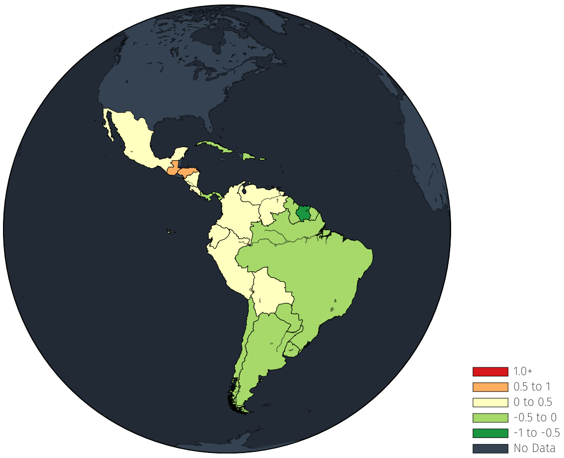
Second, improvements in social and physical *infrastructure* are likely to be critical. Such improvements can be protective to make children and their families and communities more resilient when shocks hit and able to recuperate more quickly and effectively from whatever damaages occur. The previous section gives some examples.

Third, improvements in *social safety nets* are likely to be key as well. The available literatures suggest that family resources are likely to be important aspects of prevention and remediation in the presence of climatic, pollution and natural-disaster shocks. But such family resources often are depleted rapidly by such shocks. Therefore nimble safety nets may be very important.

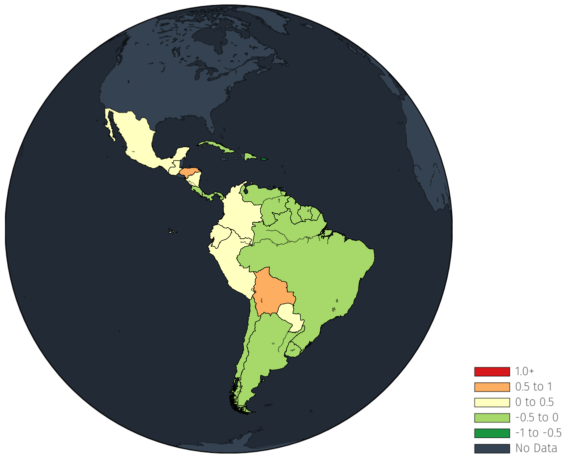
5 Conclusions

Tables and Figures

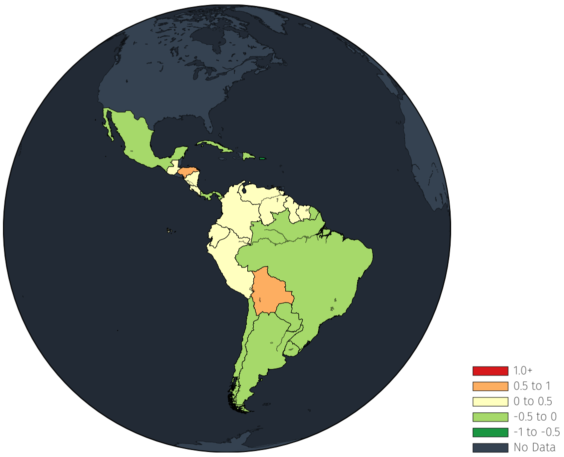
Figure 3.1: Country-level excess burden



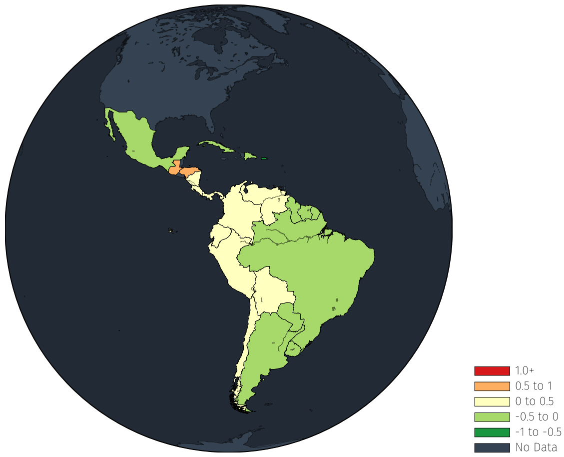
(a) 2000



(b) 2005



(c) 2010

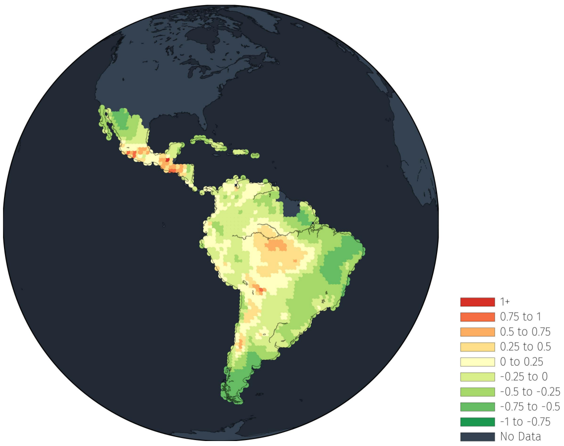


(d) 2015

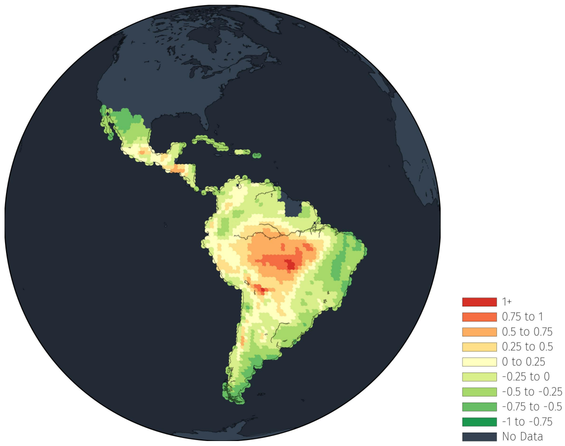
(e) 2020

Notes: These maps display cell-level air pollution burden aggregated to the country level obtained by overlapping Worldpop data on population and Van Donkelaar et al. (2021) dataset on $PM_{2.5}$ for years 2000, 2005, 2010, 2015, and 2020. Lighter colors indicate cells with smaller air pollution burden and darker colors indicates cells with more air pollution burden. Black is used to indicate missing on cell-level air pollution burden estimates, cell country label, and boundaries belonging to regions or countries outside LAC.

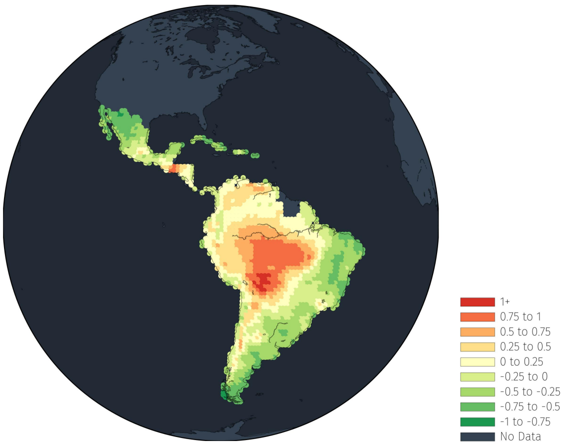
Figure 3.2: Cell-level excess burden over 1° × 1° longitude–latitude grids



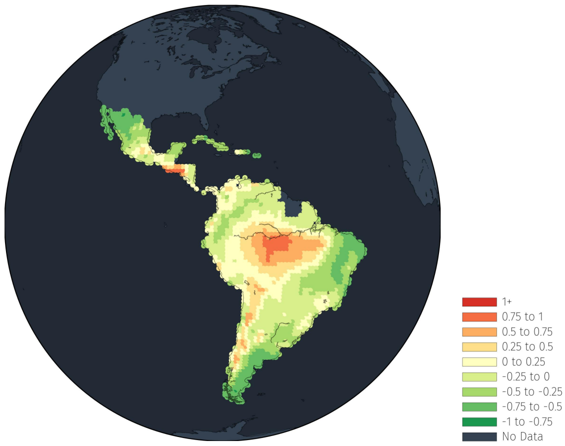
(a) 2000



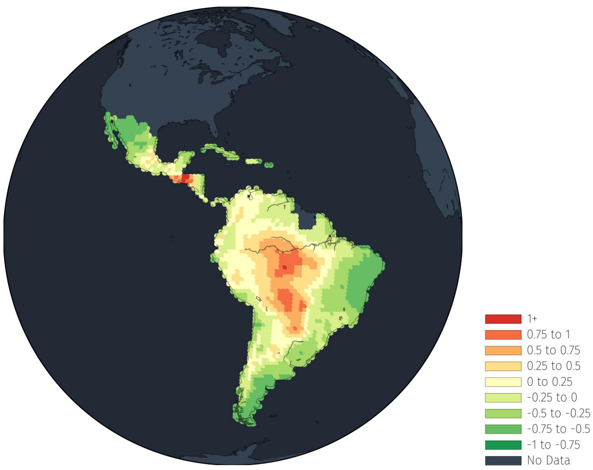
(b) 2005



(c) 2010



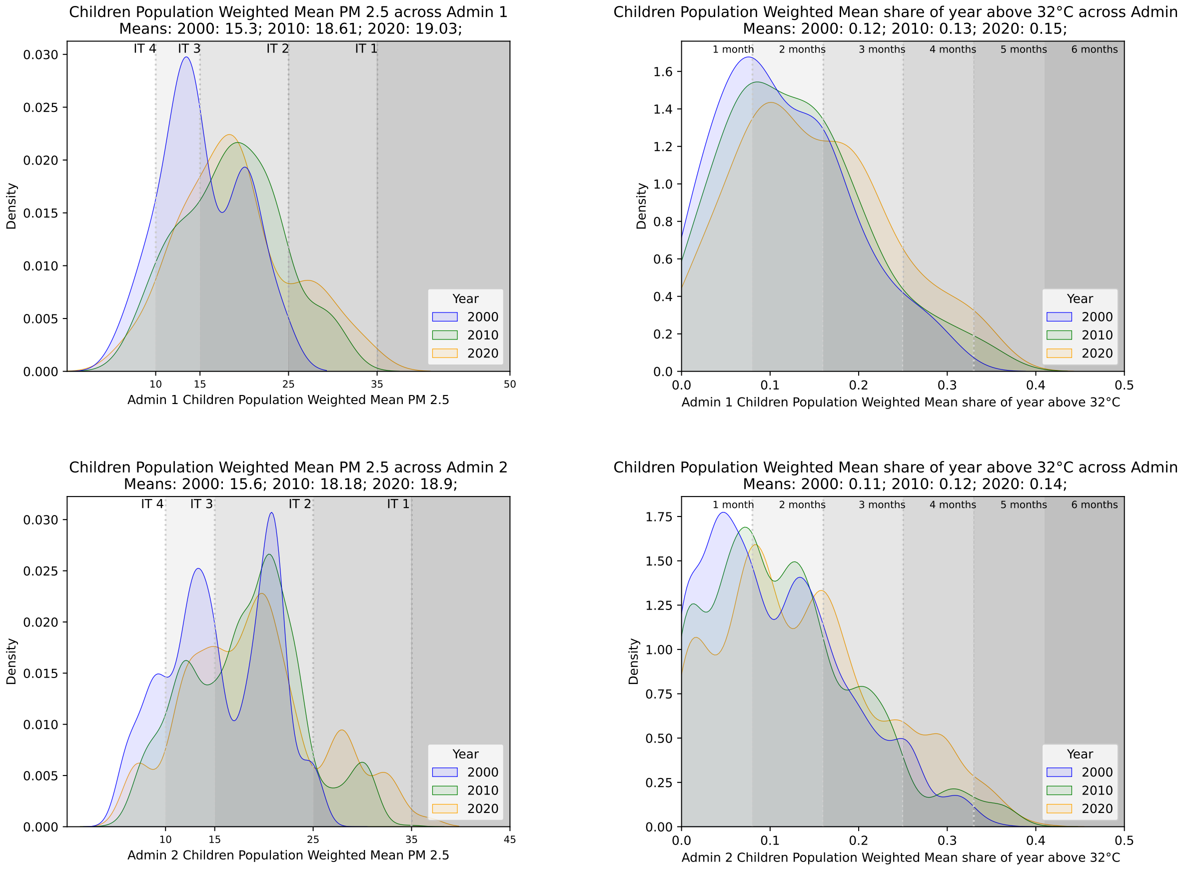
(d) 2015



(e) 2020

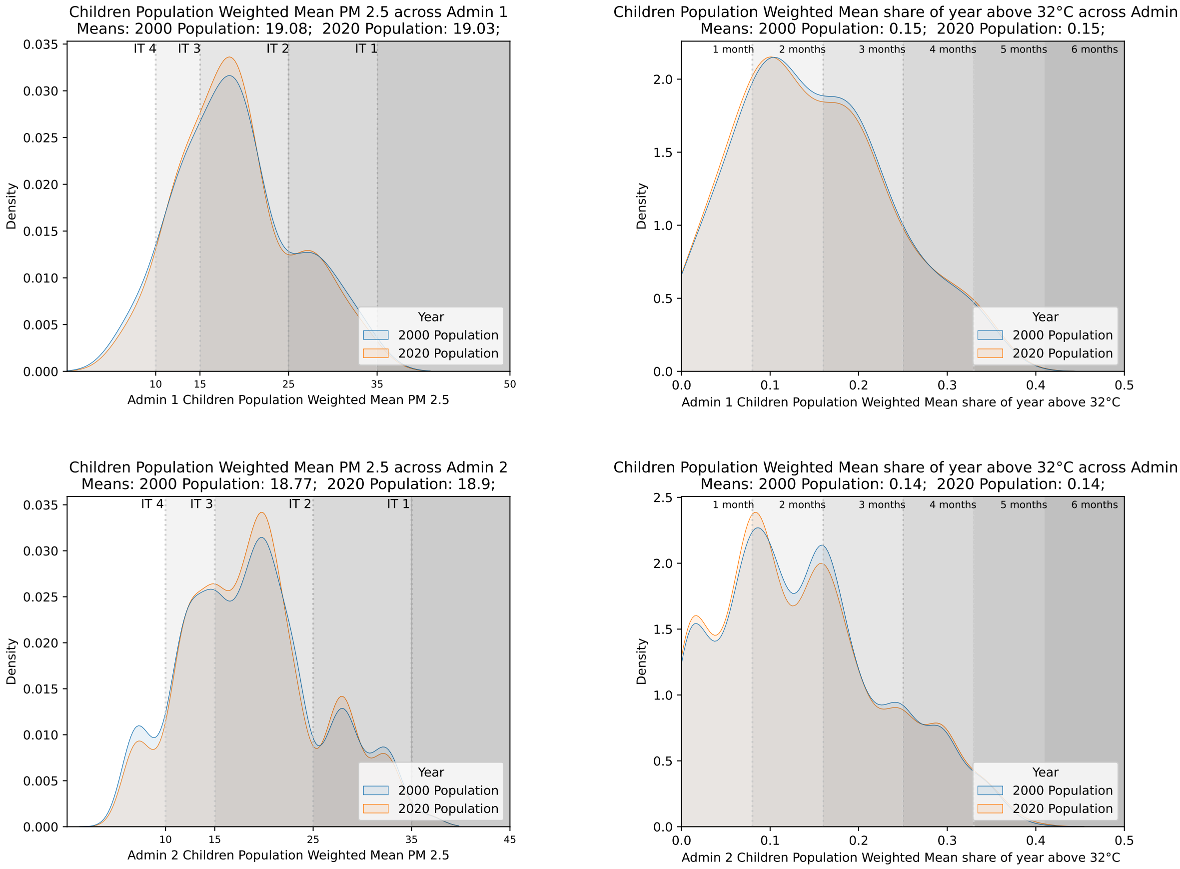
Notes: These maps display cell-level air pollution burden in $1^o \times 1^o$ resolution obtained by overlapping Worldpop data on population and Van Donkelaar et al. (2021) dataset on $PM_{2.5}$ for years 2000, 2005, 2010, 2015, and 2020. Lighter colors indicate cells with smaller air pollution burden and darker colors indicates cells with more air pollution burden. Black is used to indicate missing on cell-level air pollution burden estimates, cell country label, and boundaries belonging to regions or countries outside LAC.

Figure 3.3



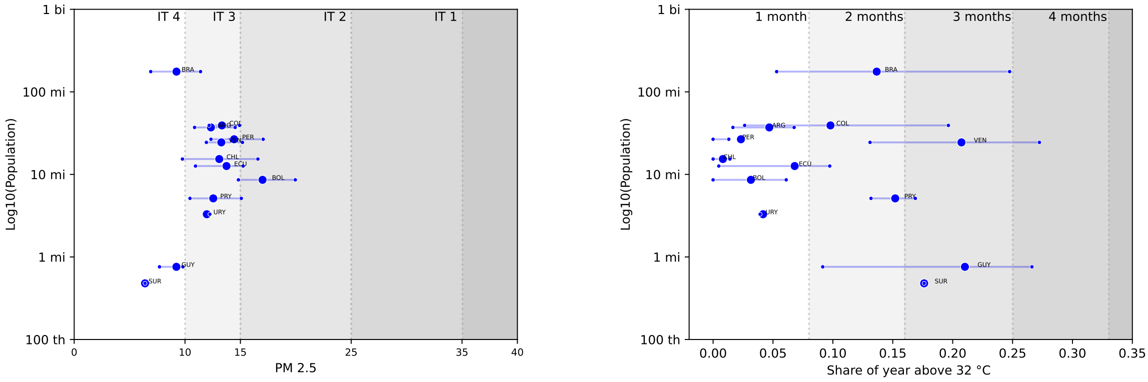
Notes:

Figure 3.4

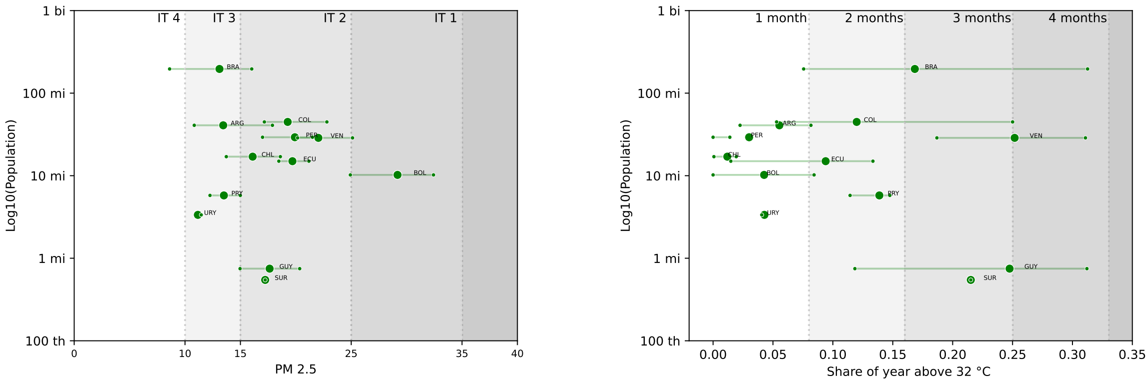


Notes:

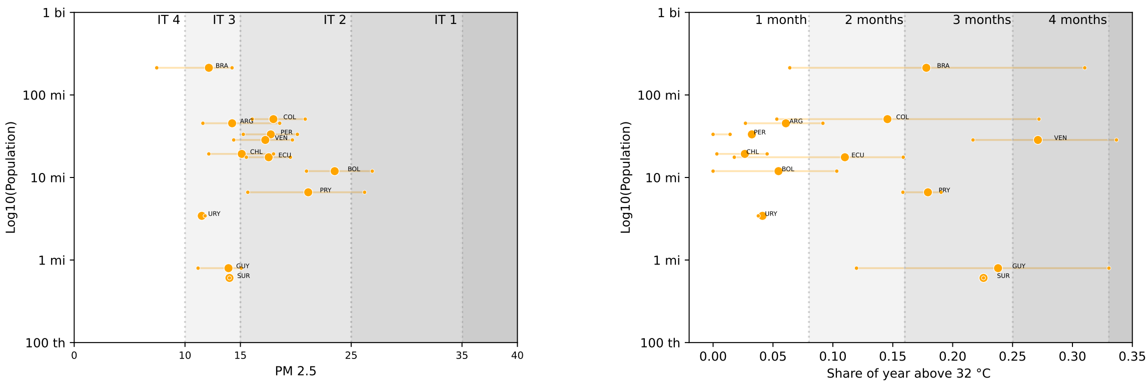
Figure 3.5: Country-specific distributional ranges. P20 (left-dot), mean (center-dot), P80 (right-dot)



2000



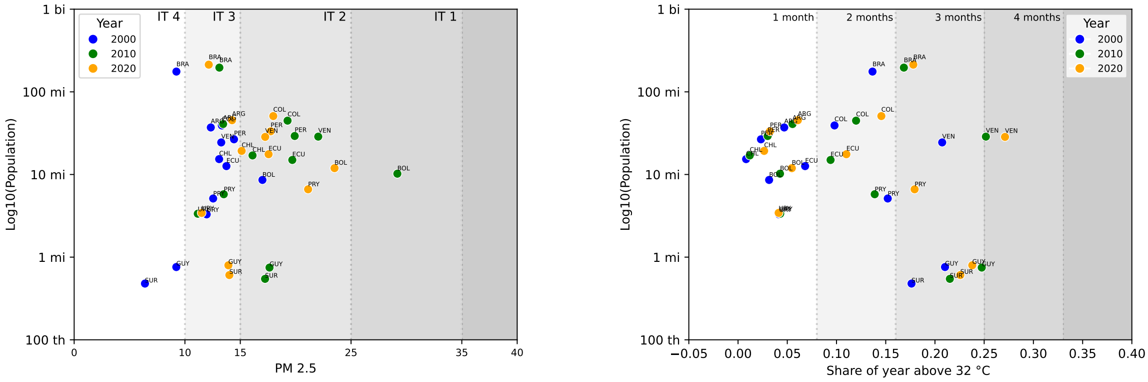
2010



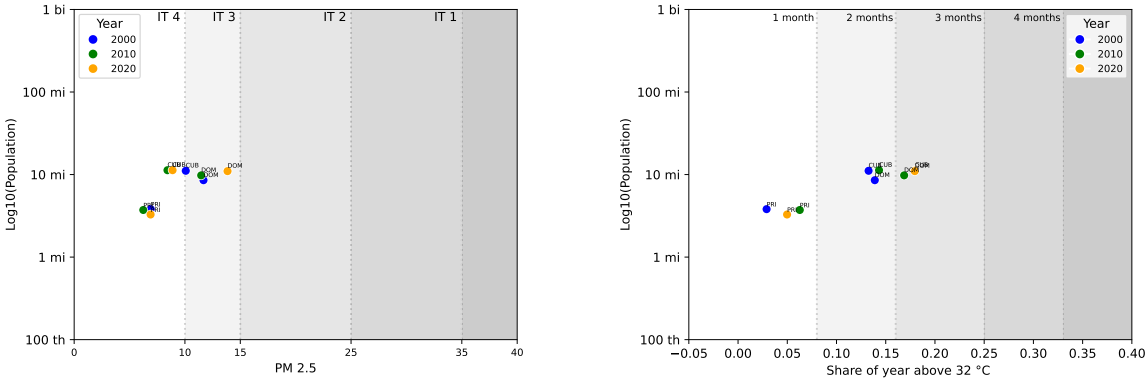
2020

Notes:

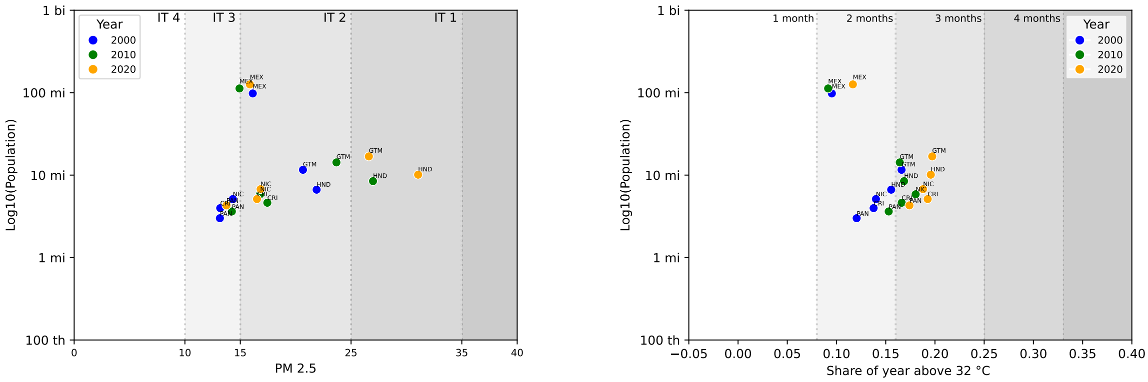
Figure 3.6: PM 2.5 and Share of year above 32 °C Country-specific means by subregion



South America



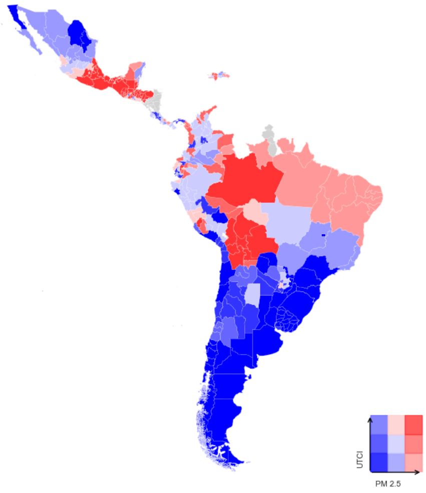
Caribbean



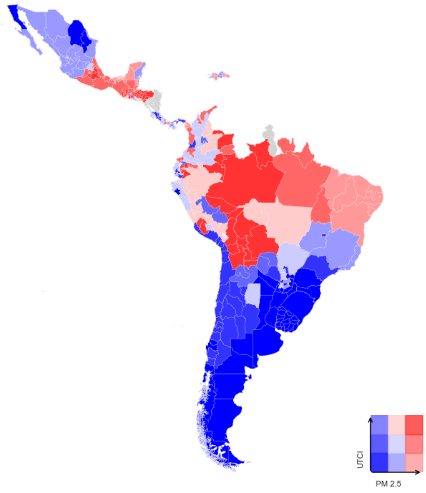
Central America

Notes:

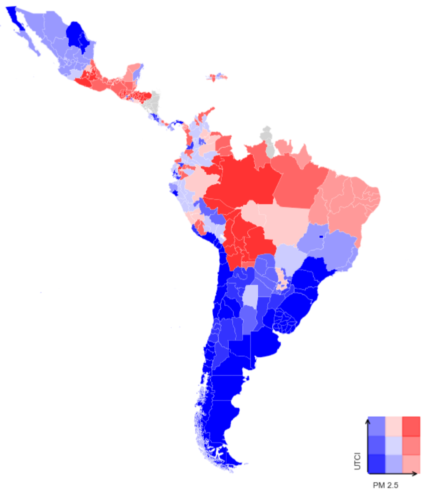
Figure 3.7: Bivariate map for PM 2.5.-UTCI mean tercile groups



(a) 2000



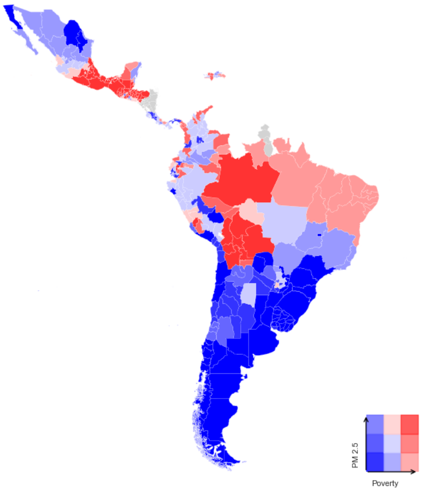
(b) 2010



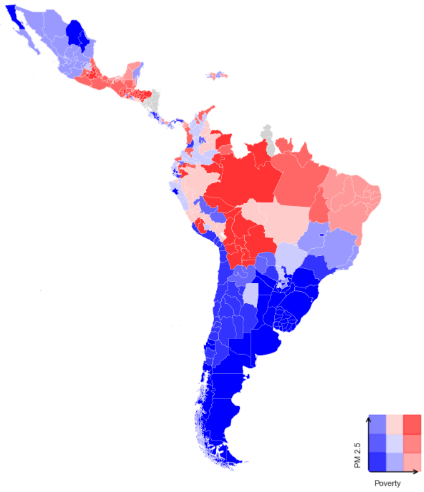
(c) 2020

Notes:

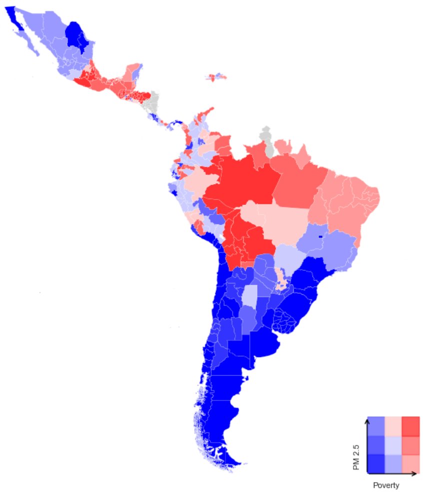
Figure 3.8: Bivariate map for Poverty-PM 2.5. mean tercile groups



(a) 2000



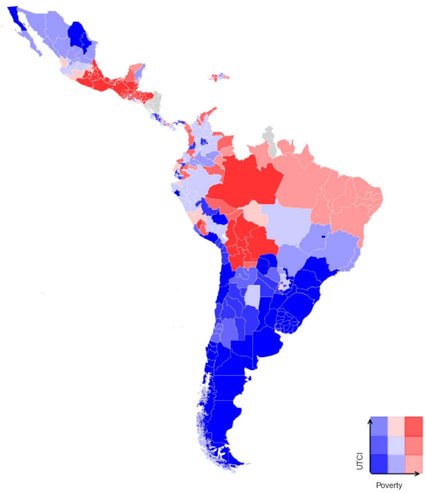
(b) 2010



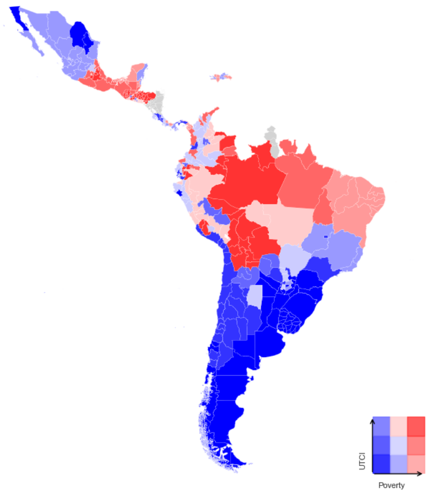
(c) 2020

Notes:

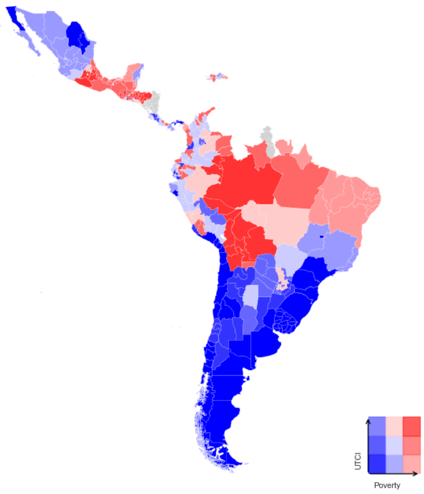
Figure 3.9: Bivariate map for Poverty-UTCI mean tercile groups



(a) 2000



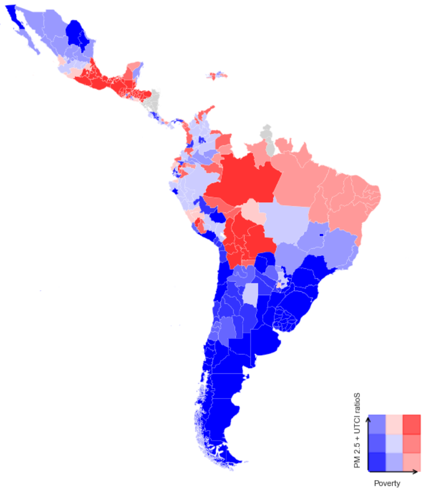
(b) 2010



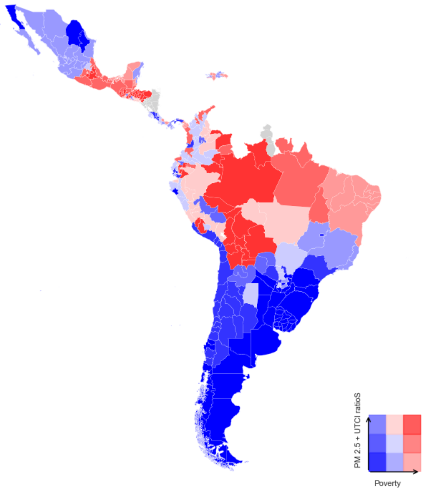
(c) 2020

Notes:

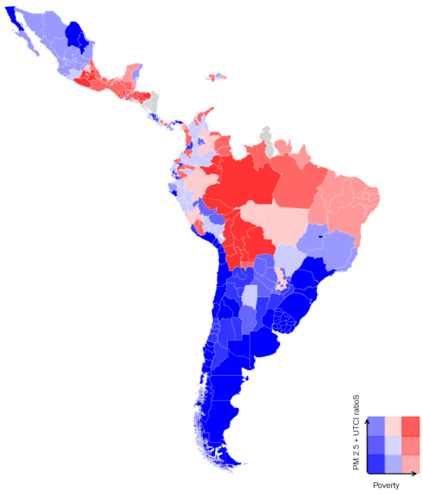
Figure 3.10: Bivariate map for Poverty-Overall exposure inequality tercile groups



(a) 2000



(b) 2010



(c) 2020

Notes:

Table 3.1: Across ADMIN 1 units statistics

Year	Mean	p10	p20	p80	p90	p80/p20	p90/p10
Panel A: PM 2.5 Exposure							
2000	15.30	9.17	11.48	20.14	21.34	1.75	2.33
2010	18.61	11.12	13.44	23.25	26.13	1.73	2.35
2020	19.03	11.54	13.86	25.51	28.21	1.84	2.44
Panel B: Share of year above 32 degrees							
2000	0.12	0.03	0.05	0.17	0.22	3.61	8.21
2010	0.13	0.03	0.06	0.19	0.24	3.33	8.15
2020	0.15	0.04	0.08	0.22	0.27	2.91	6.65

Table 3.2: Across ADMIN 2 units statistics

Year	Mean	p10	p20	p80	p90	p80/p20	p90/p10
Panel A: PM 2.5 Exposure							
2000	15.60	8.52	10.57	20.88	21.36	1.97	2.51
2010	18.18	10.61	12.43	22.80	25.14	1.83	2.37
2020	18.90	11.20	12.78	23.52	28.36	1.84	2.53
Panel B: Share of year above 32 degrees							
2000	0.11	0.01	0.04	0.17	0.22	4.74	25.92
2010	0.12	0.01	0.04	0.19	0.23	4.31	17.93
2020	0.14	0.02	0.06	0.22	0.28	3.91	14.74

Table 3.3: Admin 1 Population Shares by Exposure-Poverty quintile groups

	Children population share			Share with services $\leq$ 30 min		
	2000	2010	2020	2000	2010	2020
			PM 2.5 - UTCI			
High-High	0.31	0.26	0.30	0.15	0.18	0.16
High-Low	0.29	0.30	0.28	0.08	0.11	0.10
Low-High	0.14	0.17	0.12	0.11	0.09	0.11
Low-Low	0.19	0.21	0.23	0.06	0.05	0.05
			Poverty - UTCI			
High-High	0.30	0.26	0.28	0.15	0.15	0.14
High-Low	0.28	0.32	0.31	0.11	0.11	0.11
Low-High	0.12	0.12	0.12	0.09	0.09	0.10
Low-Low	0.23	0.23	0.23	0.05	0.05	0.05
			Poverty - PM 2.5			
High-High	0.40	0.37	0.38	0.13	0.16	0.14
High-Low	0.19	0.22	0.21	0.13	0.10	0.12
Low-High	0.17	0.16	0.17	0.08	0.11	0.11
Low-Low	0.19	0.19	0.18	0.05	0.04	0.04

Table 3.4: Admin 1 Children Population Shares by quartile

	2000	2010	2020
Mean PM 2.5			
p25	0.17	0.19	0.17
p50	0.17	0.19	0.18
p75	0.22	0.27	0.28
p100	0.38	0.28	0.30
Mean Share of year above 32 degrees			
p25	0.18	0.16	0.16
p50	0.30	0.35	0.35
p75	0.27	0.24	0.25
p100	0.19	0.18	0.18
Mean PM 2.5 p80/p20			
p25	0.18	0.20	0.20
p50	0.19	0.19	0.19
p75	0.32	0.25	0.29
p100	0.25	0.30	0.26
Mean Share of year above 32 degrees p80/p20			
p25	0.15	0.16	0.17
p50	0.18	0.19	0.18
p75	0.33	0.34	0.31
p100	0.27	0.24	0.27
Mean PM 2.5 p90/p10			
p25	0.19	0.15	0.16
p50	0.19	0.23	0.24
p75	0.26	0.24	0.23
p100	0.30	0.31	0.30
Mean Share of year above 32 degrees p90/p10			
p25	0.12	0.12	0.12
p50	0.21	0.19	0.21
p75	0.34	0.36	0.33
p100	0.27	0.26	0.28
Overall environmental inequalities			
p25	0.16	0.18	0.19
p50	0.20	0.17	0.19
p75	0.26	0.25	0.24
p100	0.28	0.29	0.28

Table 3.5: LAC country child air pollution and heat exposure ranking in 2010

Country name	Air pollution by aerosols: Child (0-5) mean AOD exposure ($0 \leq \text{AOD} \leq 1$)	Air pollution by aerosols: LAC child AOD rank	Heat stress exposure: Child (0-5) mean annual share of time over 32 UTCI degrees	Heat stress exposure: LAC child temperature rank
Panel A: High income				
Antigua and Barbuda (ATG)	0.221	14	4.4%	11
Bahamas, The (BHS)	0.230	20	11.0%	21
British Virgin Islands (VGB)	0.218	13	3.9%	8
Chile (CHL)	0.106	1	0.6%	2
Guyana (GUY)	0.253	25	27.5%	36
Panama (PAN)	0.277	31	14.7%	23
Puerto Rico (PRI)	0.244	22	6.2%	13
Trinidad and Tobago (TTO)	0.280	32	15.9%	27
Turks and Caicos Islands (TCA)	0.179	5	4.4%	10
Uruguay (URY)	0.144	4	3.4%	6
Panel B: Upper middle income				
Argentina (ARG)	0.138	3	5.0%	12
Belize (BLZ)	0.274	29	19.8%	32
Brazil (BRA)	0.194	7	15.6%	25
Colombia (COL)	0.344	36	10.6%	19
Costa Rica (CRI)	0.246	23	16.6%	28
Dominican Republic (DOM)	0.225	16	16.8%	29
Ecuador (ECU)	0.297	34	7.8%	17
Grenada (GRD)	0.260	28	6.5%	14
Guatemala (GTM)	0.223	15	10.1%	18
Jamaica (JAM)	0.229	19	10.8%	20
Mexico (MEX)	0.187	6	7.0%	16
Paraguay (PRY)	0.255	27	14.4%	22
Peru (PER)	0.228	18	3.8%	7
St. Lucia (LCA)	0.216	12	2.6%	3
Suriname (SUR)	0.274	30	26.3%	35
Panel C: Lower middle income				
Bolivia (BOL)	0.255	26	6.6%	15
Haiti (HTI)	0.216	11	19.1%	31
Honduras (HND)	0.204	8	15.9%	26
Nicaragua (NIC)	0.227	17	18.3%	30
Panel D: Without World Bank income group designation				
Anguilla (AIA)	0.234	21	3.3%	5
Falkland Islands (FLK)	0.112	2	0.0%	1
French Guiana (GUF)	0.249	24	25.5%	34
Martinique (MTQ)	0.215	10	4.3%	9
Montserrat (MSR)	0.211	9	3.1%	4
St. Eustatius (BES)	0.292	33	15.3%	24
Venezuela (VEN)	0.314	35	22.0%	33

Note: A rank of 1 indicates that the country has the least child (0-5) air pollution by aerosol or heat exposure among LAC countries. Country income groups are based on World Bank classifications. Results are based on within-country distributions of cell-level child (0-5) population distribution as well as cell-level air pollution by aerosols and UTCI temperature distributions. Atmospheric pollution by aerosols is important to human health and well-being because higher amounts of aerosol particles degrade visibility and can also damage health, especially when there is a higher concentration of $PM_{2.5}$ particles that are smaller than 2.5 micrometers. Aerosol Optical Depth (AOD) is a satellite-based measure that captures the composition, sizes and concentration of aerosols by measuring the magnitudes atmospheric light reflection and absorption across the globe. AOD < 0.1 indicates crystal clear sky and AOD of 1 indicates very hazy conditions. Heat is based on Universal Thermal Climate Index (UTCI), which provides an integrative measure of the human-perceived equivalent temperature, taking into account factors like air temperature, humidity, wind speed, and radiant heat. UTCI between 32 degree C and 38 degree C indicate strong heat stress. Results are visualized, in units of excess exposures, on the Maps in Figure **??** for air pollution by aerosol exposures, and in Figure **??** for heat exposures.

Tables and Figures (Existing data)

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ONLINE APPENDIX

Extreme Heat and Air Pollution Risks for Early Childhood Development in Latin America and the Caribbean

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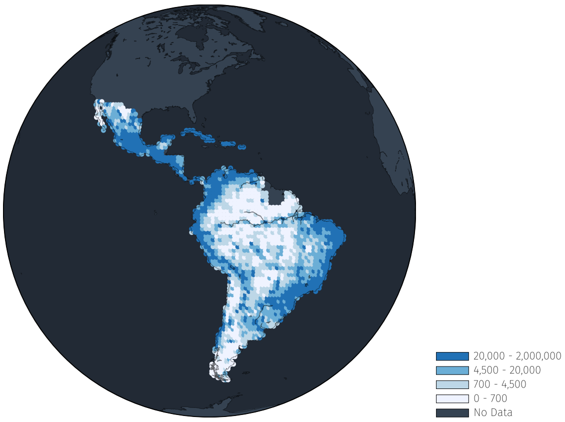
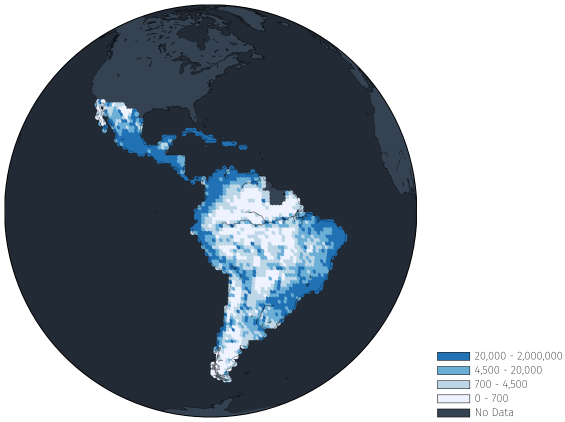
A Additional Figures and Tables (online)

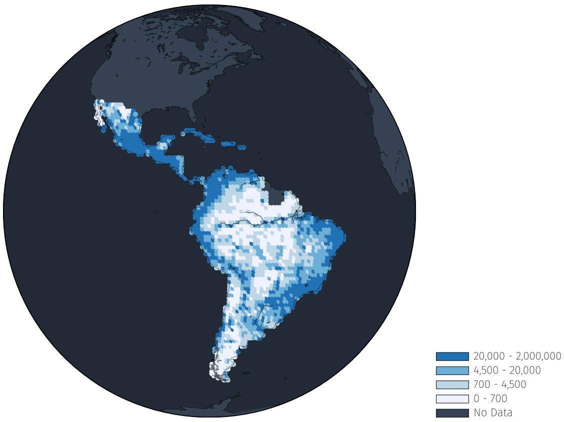
Figure A.1: Cell-level population estimates over $1° \times 1°$ longitude–latitude grids



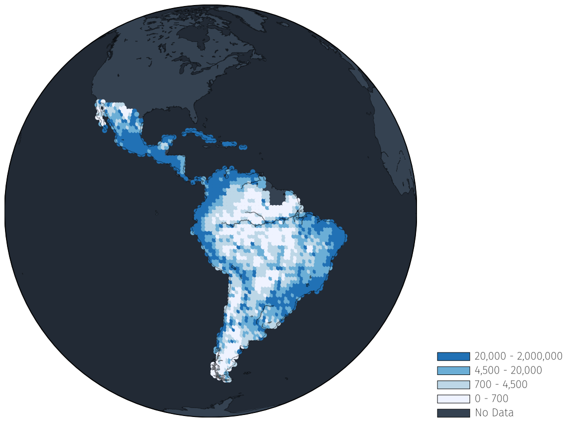
(a) 2000



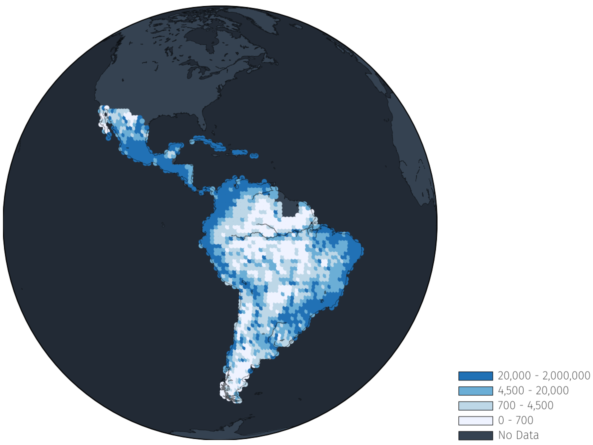
(b) 2005



(c) 2010



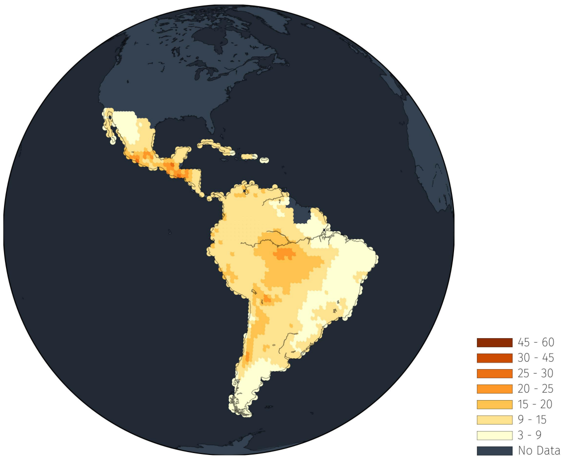
(d) 2015



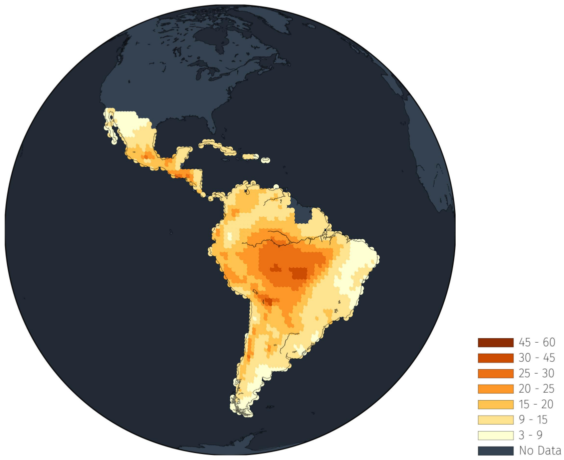
(e) 2020

Notes: These maps display cell-level population estimates in $1^o \times 1^o$ resolution using Worldpop data for years 2000, 2005, 2010, 2015, and 2020. Lighter colors indicate less populated cells and darker colors indicates more populated cells. Black is used to indicate missing on cell-level population estimates, cell country label, and boundaries belonging to regions or countries outside LAC.

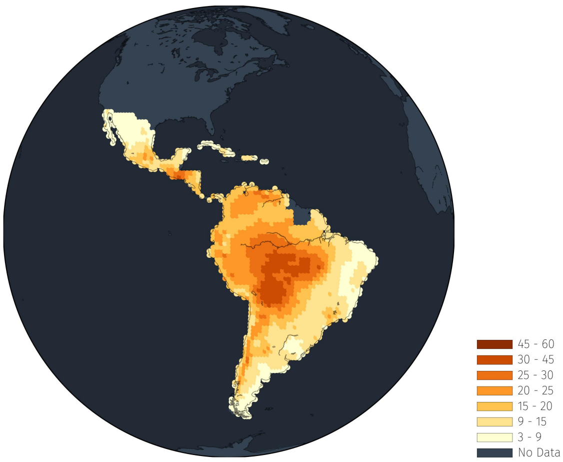
Figure A.2: Cell-level $PM_{2.5}$ level over $1^\circ \times 1^\circ$ longitude–latitude grids



(a) 2000



(b) 2005



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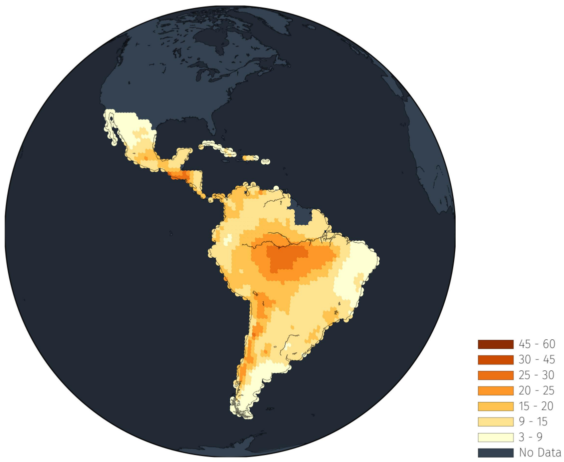
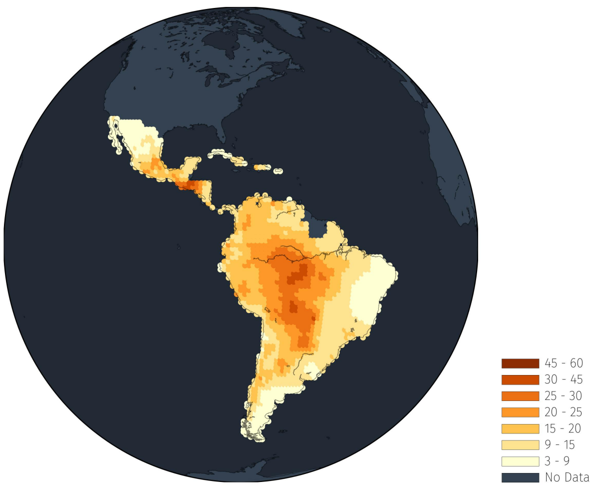


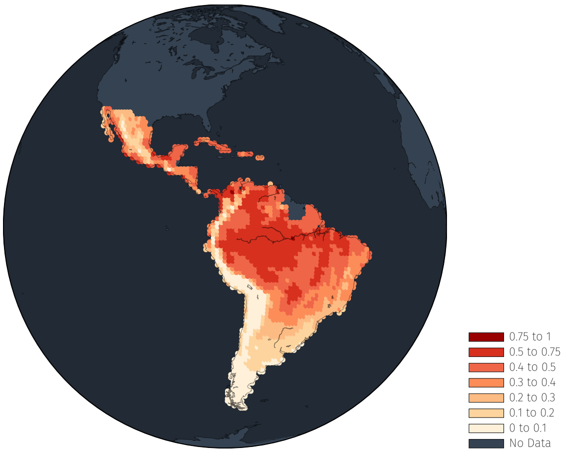
(d) 2015



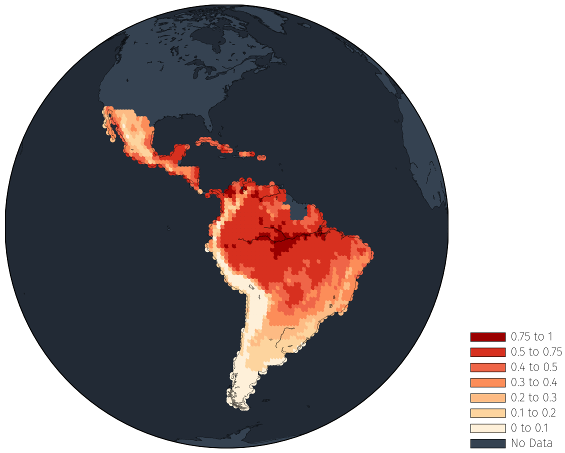
(e) 2020

Notes: These maps display cell-level $PM_{2.5}$ levels in $1^o \times 1^o$ resolution using Van Donkelaar et al. (2021) dataset for years 2000, 2005, 2010, 2015, and 2020. Lighter colors indicate lower levels of air pollution levels and darker colors indicates more higher levels of pollution. Black is used to indicate missing on cell-level air pollution level, cell country label, and boundaries belonging to regions or countries outside LAC.

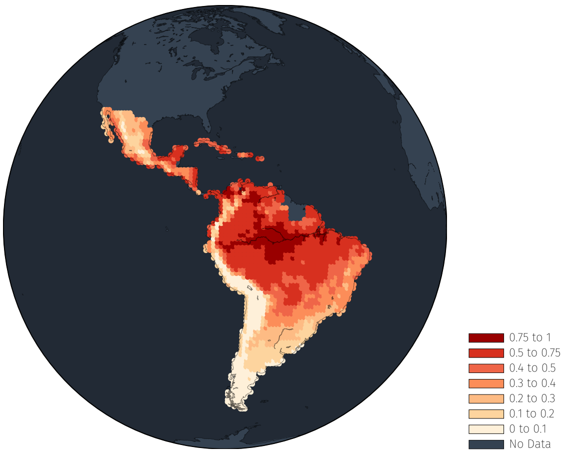
Figure A.3: Cell-level share of time temperature was in excess of UTCI 26 over $1^\circ \times 1^\circ$ longitude–latitude grids



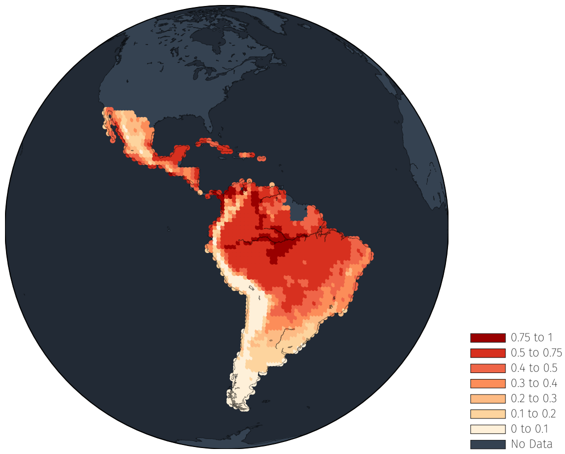
(a) 2000



(b) 2005



(c) 2010



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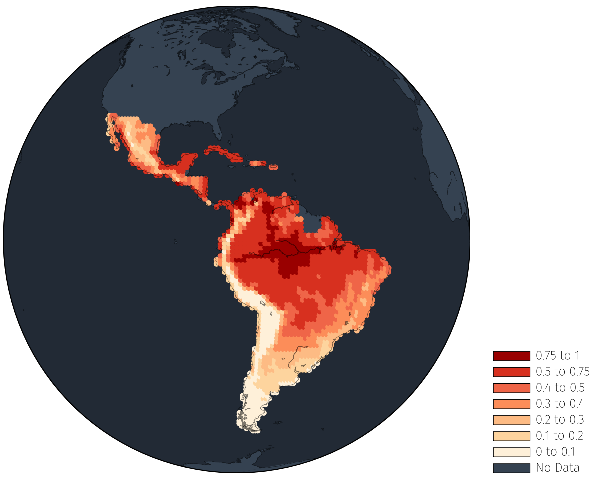

(e) 2020

Notes: These maps display cell-level share of time temperature was in excess of UTCI 26 in $1^o \times 1^o$ resolution using UTCI dataset from ERA5 for years 2000, 2005, 2010, 2015, and 2020. Lighter colors indicate cell with smaller share of time temperature was in excess of UTCI 26 in a particular year and darker colors indicates more share of time above the same threshold. Black is used to indicate missing on cell-level time temperature was in excess of UTCI 26, cell country label, and boundaries belonging to regions or countries outside LAC.